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Radial variation in partial compression properties perpendicular to the grain of Japanese larch (*Larix kaempferi*)

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Abstract This study investigated the densities, average width of annual rings, and partial compression stresses at 5 % strain perpendicular to the grain of air-dried wood specimens, which were continuous in the radial direction from the pith and were obtained from Japanese larch (*Larix kaempferi*) trees with different diameters at breast height in the same stand, to evaluate the radial variations in partial compression properties perpendicular to the grain. The air-dried densities of the wood increased with the distance from the pith. The average width of annual rings of the wood tended to decrease with increasing distance from the pith and those of medium- and large-diameter trees seemed to increase near the pith. The partial compression stresses at 5 % strain in the tangential loading direction tended to increase with the distance from the pith and with air-dried wood density. However, in the radial loading direction, this tendency was not observed. The partial compression stresses at 5 % strain in the radial loading direction tended to be low in wood with a small average width of annual rings. These results indicate that the factors affecting the radial variations in the partial compression stress at 5 % strain differ depending on the loading directions.

Keywords *Larix kaempferi* · Compression properties · Radial variation · Air-dried wood density · Annual ring width

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Introduction

Wood is a natural material that has high Young's modulus and strength in the longitudinal direction, although its density is relatively low. For a long time, it has been used mainly as a building material in Japan, where there are many forests. The ages of most planted forests in Japan are now sufficient for procuring wood material. To use these forest resources more effectively, an understanding of the properties of wood and ways to take advantage of these properties is important.

The mechanical properties of wood in the longitudinal direction are important properties in structural elements such as beams. It is well known that juvenile wood whose xylem typically extends up to approximately 10–15 annual rings from the pith and mature wood whose xylem extends beyond 10–15 annual rings from the pith in the case of softwood have different mechanical properties in the longitudinal direction. The longitudinal mechanical properties, e.g., Young's modulus and strength, of juvenile wood are reported to be lower than those of mature wood [1–4]. This difference has been attributed to the differences in the wood densities and cell-wall structures, such as those in the microfibril angles in the S_2 layers, between juvenile and mature wood [1–5].

There have been some reports that the partial compression properties perpendicular to the grain, which are important properties for bed sills in the conventional Japanese construction method, also vary from pith to bark. Kretschmann [6] investigated how varying proportions of juvenile wood and ring orientations influenced the compression properties perpendicular to the grain of loblolly pine (*Pinus taeda*). He reported that the compression stress perpendicular to the grain is more sensitive to the juvenile wood content for loads applied to a radial surface than those to a tangential surface.

Morita and Aratake [7] reported that the partial compression properties perpendicular to the grains of laminated wood of Obi-sugi (*Cryptomeria japonica*) consisting of laminae with pith are superior to those of laminated wood consisting of laminae without pith. Nagaishi et al. [8] investigated the effect of the distance from the pith and of ring orientation on the partial compression properties perpendicular to the grain to reveal the reason behind the phenomenon reported by Morita and Aratake [7]. They reported that the effect of the ring orientation is minimal and that the partial compression properties perpendicular to the grain of the juvenile wood near the pith are higher than those of the mature wood. Their reports indicated the possibility that juvenile wood was not necessarily inferior to mature wood when used as a bed sill.

To obtain the lumber or the glued laminated lumber suitable for bed sills, it is important to investigate the radial variation in the partial compression properties perpendicular to the grain. However, unlike the variations in the mechanical properties of wood in the longitudinal direction, the radial variations in the partial compression properties of wood have rarely been investigated.

Therefore, in this study, the densities, average width of annual rings (ARW), and partial compression stress perpendicular to the grain of air-dried wood specimens, which were continuous in the radial direction from the pith and were obtained from Japanese larch trees with different diameters at breast height (DBH) in the same stand, were investigated by performing partial compression tests. This investigation enabled us to study the differences in the partial compression properties perpendicular to the grain from the pith to the bark of Japanese larch, which has a relatively high strength among the planted Japanese wood species.

Materials and methods

Sample trees

Eighteen logs of trees with different DBH were felled at a 51-year-old stand of Japanese larches in Kyougoku, Hokkaido, Japan, in October 2010. The dynamic Young's modulus of the first logs, each with a length of 385 cm, was measured by the longitudinal vibration method based on the method reported by Koizumi et al. [9] after measuring the diameters at the butt end and the top end, and the weight of each log. The specific frequency was measured using a data logger (KEYENCE Corporation, NR-500, NR-CA04) and fast Fourier transform (FFT) analysis software (KEYENCE Corporation, WAVE LOGGER Ver. 3.03). The following formula was used to calculate the dynamic Young's modulus:

Table 1 Properties of logs

Log no.	DBH (cm)	Density (kg/m^3)	E_{fr} (GPa)
S1	15.8	499	7.28
S2	17.3	585	9.93
S3	18.7	598	8.54
M1	24.8	596	8.67
M2	26.5	606	9.20
M3	25.9	613	8.97
L1	38.4	584	8.53
L2	41.3	595	7.11
L3	42.0	552	6.46

DBH diameter at breast height, *Density* apparent density, E_{fr} dynamic Young's modulus

$$E_{\mathrm{fr}} = 4l^2 f^2 \rho$$

Here, l is the length of the log, f is the specific frequency, and ρ is the apparent density, which was calculated using the following equations:

$$\rho = W/V$$

$$V = \pi l/12(D_{\mathrm{b}}^2 + D_{\mathrm{b}}D_{\mathrm{t}} + D_{\mathrm{t}}^2)$$

Here, W is the weight, V is the volume, D_{b} is the diameter of the butt end, and D_{t} is the diameter of the top end.

The logs were classified according to their DBH into three groups: small (DBH < 20 cm), medium (DBH = 20–30 cm), and large (DBH > 30 cm). Three logs with different Young's modulus were selected from each group. Thus, nine logs were used in the following tests. Table 1 lists the properties of the logs.

Wood samples

After measuring the dynamic Young's modulus, the logs were cut at approximately 120 and 370 cm from the butt end (Fig. 1). They were then lumbered into 250-cm long and 6-cm wide boards that included the pith; these boards were then kiln dried. They were then conditioned at 20 °C and 65 % RH for more than 1 month after being kiln dried. Then, they were cut at 40–210 cm from the butt end and lumbered into boards with lengths and widths of approximately 170 and 2 cm, respectively, as shown in the figure. The number and the width of the annual rings were measured on the transverse face of the butt end of the boards. Ten sets of wood specimens (20 (T) × 20 (R) × 60 (L) mm) that were continuous in the radial direction were prepared from each board. These specimens were further conditioned at 20 °C at 65 % RH

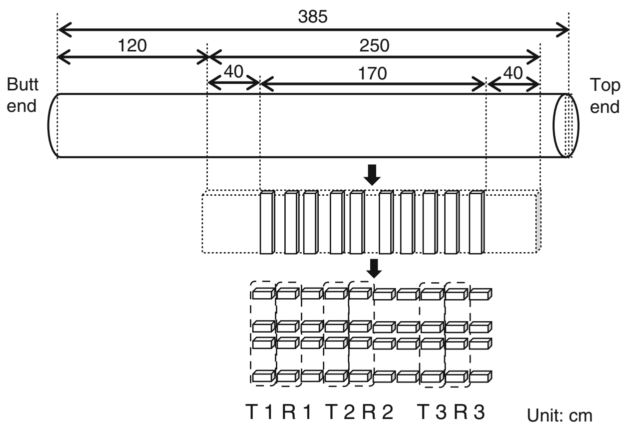


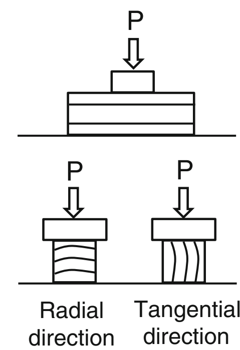
Fig. 1 Sample preparation procedure for the partial compression tests perpendicular to the grain specimens. *T* specimen for partial compression test in the tangential direction, *R* specimen for partial compression test in the radial direction

for more than 1 month. For testing the partial compression perpendicular to the grain for each tree, six sets of wood specimens that were continuous in the radial direction and that contained fewer knots than others were selected.

Partial compression tests perpendicular to the grain

The weight, dimensions, and width of the annual rings of the wood specimens after conditioning were measured before testing. Partial compression tests perpendicular to the grain were performed according to JIS Z 2101 [10]. The samples were loaded in the tangential and radial directions (Fig. 2). From each tree, three sets of specimens continuous in the radial direction were used in tests for the tangential loading direction and three more were used in tests for the radial loading directions. A universal testing machine, TENSILON RTD-2410 (Orientic Corporation), was used for loading, and efforts were made to keep the average loading speed under 0.98 N/mm^2 per minute. The displacement was measured using 10-mm range displacement transducers attached to both ends of the loading plate, and the average of the two values was calculated. Stress was calculated by dividing the load by the width of the specimen and the width of the loading plate (20 mm). Partial compression stress at 5 % strain ($\sigma_{5\ \%}$) was defined as the stress at 5 % strain of the height of the wood specimens. The air-dried density of wood specimens was calculated from the weight and dimensions of the specimens before the partial compression tests, and the ARW was calculated from the width of the annual rings of the specimens. The moisture content was also calculated from the weights before the tests and those after oven drying.

Fig. 2 Scheme of partial compression test perpendicular to the grain of wood specimens. *P* load



Results and discussion

Properties of wood samples

Table 2 lists the average values of density, ARW, and $\sigma_{5\%}$ of the air-dried wood specimens in the tangential and radial loading directions. The average ARW of the wood specimens prepared from logs with larger diameters tended to be higher. The average values of air-dried density and ARW of wood specimens prepared from the same log were almost the same in both the tangential and the radial loading directions. However, the average $\sigma_{5\%}$ value in the tangential loading direction was greater than that in the radial loading direction in each log.

Ido et al. [11] investigated the partial compression properties perpendicular to the grain of five softwood species and reported that $\sigma_{5\%}$ was greater in the tangential direction than in the radial direction for Japanese cedar (*Cryptomeria japonica*), Japanese larch, Japanese red pine (*Pinus densiflora*), and Dahurian larch (*Larix gmelinii*). According to their report, $\sigma_{5\%}$ of Japanese larch was 11.3 N/mm^2 in the tangential loading direction and 7.29 N/mm^2 in the radial loading direction. These values are different from the values listed in Table 2. However, the $\sigma_{5\%}$ values in the tangential loading directions were greater than those in the radial loading directions—a tendency identical to that reflected in Table 2. This indicates that the partial compression properties of Japanese larch wood exhibits anisotropy in the loading direction.

Radial variations in the density and ARW of the air-dried wood

Figure 3 shows the radial variations in the density and ARW of the air-dried wood specimens of logs with different diameters. The density of the air-dried wood specimens tended to increase with the distance from the pith (Fig. 3a–c). The increase in the density with the distance from the pith was gradual in the case of larger-diameter logs (Fig. 3a–c). The ARW of the wood specimens tended to decrease with increasing distance from the pith (Fig. 3d–f), but the ARW of the specimens obtained from medium- and large-diameter logs seemed to increase near the pith.

Table 2 Results of density, ARW, moisture content, and partial compression stress at 5 % strain perpendicular to the grain of air-dried wood samples

Log no.	Loading direction	n	Density (g/cm^3)		ARW (mm)		MC (%)		$\sigma_{5\%}$ (N/mm^2)	
			Average	SD	Average	SD	Average	SD	Average	SD
S1	T	15	0.45	0.04	3.46	1.01	11.58	0.24	8.63	1.41
	R	14	0.45	0.04	3.59	0.94	11.66	0.27	7.58	1.37
S2	T	16	0.53	0.07	3.13	1.25	12.14	0.23	10.70	1.54
	R	15	0.52	0.06	3.20	1.02	12.15	0.49	7.60	0.71
S3	T	17	0.46	0.06	4.45	1.55	11.75	0.22	8.07	1.74
	R	17	0.45	0.07	4.23	1.28	11.73	0.46	7.05	0.82
M1	T	24	0.50	0.07	5.34	2.31	11.91	0.34	11.19	2.45
	R	24	0.50	0.07	5.02	2.54	11.78	0.33	9.29	2.15
M2	T	26	0.51	0.08	4.47	2.26	12.27	0.33	10.73	2.59
	R	26	0.50	0.08	4.37	2.14	12.17	0.29	8.80	1.32
M3	T	27	0.51	0.08	4.43	2.24	12.40	0.70	10.24	2.55
	R	26	0.52	0.07	4.64	2.38	12.60	0.52	8.99	1.48
L1	T	40	0.51	0.05	5.62	2.10	12.46	0.58	11.49	2.16
	R	41	0.50	0.05	5.71	2.33	12.15	0.44	9.23	1.35
L2	T	45	0.51	0.05	5.81	1.82	12.88	0.32	9.99	2.14
	R	45	0.51	0.05	5.75	1.92	12.76	0.31	8.67	1.38
L3	T	45	0.46	0.04	6.00	2.11	11.68	0.93	9.35	1.90
	R	44	0.46	0.04	5.70	2.28	11.79	0.79	8.44	2.04

n number of specimens, *Density* air-dried wood density, *ARW* average width of annual rings, *MC* moisture content, $\sigma_{5\%}$ partial compression stress at 5 % strain perpendicular to the grain, *T* tangential direction, *R* radial direction

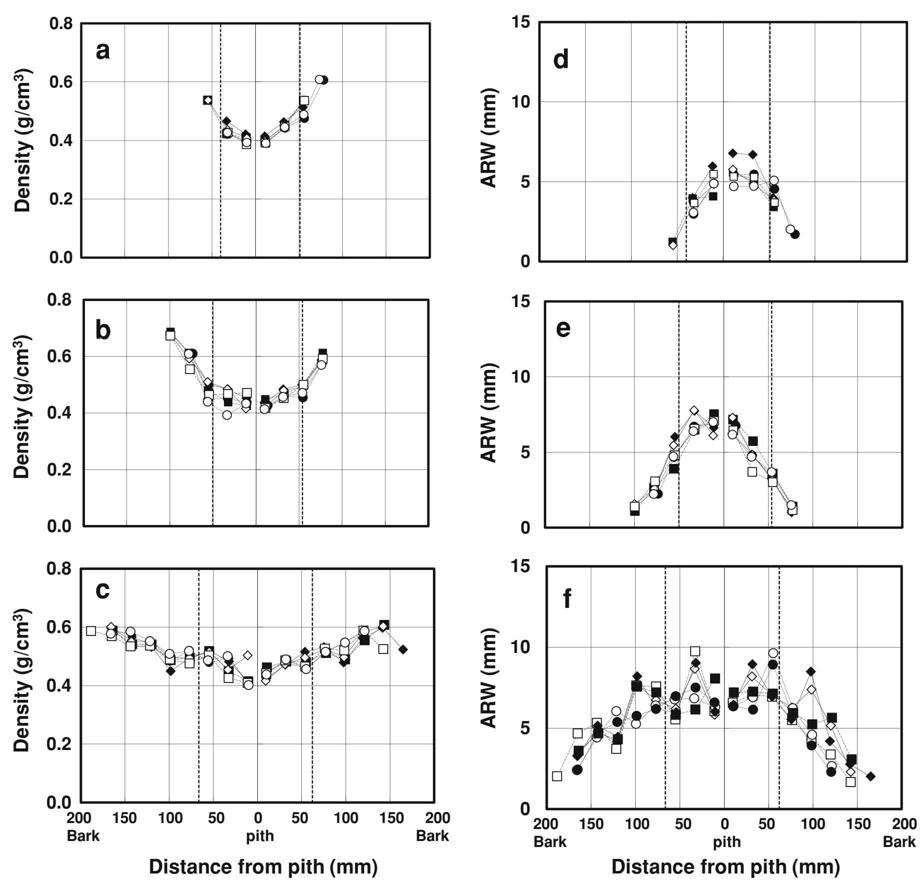


Fig. 3 Relationship among air-dried wood density, ARW, and distance from pith. **a** Densities of specimens from S3, **b** densities of specimens from M2, **c** densities of specimens from L2, **d** average width of annual rings of specimens from S3, **e** average width of annual rings of specimens from M2, **f** average width of annual rings of specimens from L2. *Density* air-dried wood density, *filled diamond* T1, *filled square* T2, *filled circle* T3, *open diamond* R1, *open square* R2, *open circle* R3, *T* specimen for the partial compression test in the tangential direction, *R* specimen for the partial compression test in the radial direction, *dashed line* distance of 10th annual ring from the pith

Koizumi et al. [12] investigated the growth-ring parameters by X-ray densitometry and the mechanical properties of Japanese larch trees from different provenances. They observed that the widest annual ring width was observed within a few rings of the pith, beyond which the width rapidly decreased in the core wood section. The highest ARW of the specimens from medium- and large-diameter trees was observed within 10 rings from the pith, as shown in Fig. 3d–f. This result is similar to that obtained by Koizumi et al. [12].

Figure 4 shows the relationship between the ARW and the density of the air-dried wood specimens. In medium- and small-diameter trees, the density of the air-dried wood specimens was almost constant for specimens with an ARW greater than 5 mm, and the density of the air-dried wood specimens increased with decreasing ARW for specimens with an ARW less than 5 mm.

Koizumi et al. [12] reported that with an increase in the cambial age (determined from the number of rings from the pith) from the 5th to 15th, the annual ring width decreased from approximately 7 mm to 3 mm and the latewood percentage increased from approximately 14 % to 34 %. In addition, the earlywood density was almost stable at approximately 400 kg/m^3, whereas the latewood density increased from approximately 750 kg/m^3 to 900 kg/m^3, and the average wood density within a ring increased from approximately 450 kg/m^3 to 540 kg/m^3.

On the basis of their report, increases in the density of the air-dried wood specimens with the distance from the pith, as shown in Fig. 3, would be mainly due to the changes in the structures of annual rings, such as an increase in the latewood percentage and in the density of latewood. The differences in the densities of wood specimens with the same ARW, as shown in Fig. 4, may be attributed to the difference in the structures of the annual rings. In addition, the presence of extractives such as arabinogalactan may also affect the wood density in the air-dried condition [12, 13].

Radial variation in $\sigma_{5\%}$ of the air-dried wood

Figure 5 shows the representative partial compression stress–strain curves of the air-dried wood specimens in the

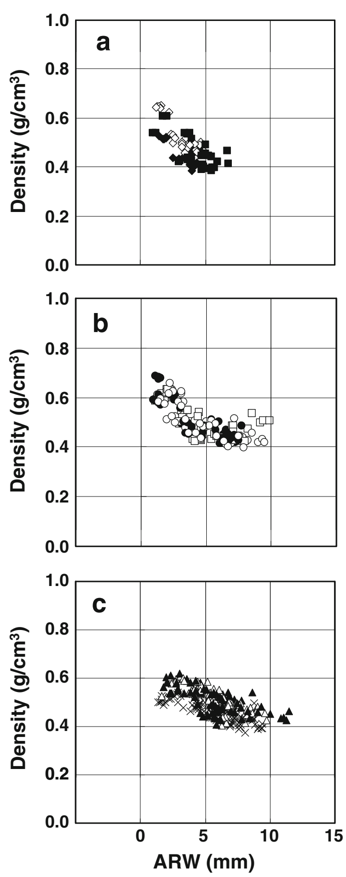


Fig. 4 Relationship between ARW and air-dried wood densities. **a** Specimens from small-diameter logs, **b** specimens from medium-diameter logs, **c** specimens from large-diameter logs. *Density* air-dried wood density, *filled diamond* S1, *open diamond* S2, *filled square* S3, *open square* M1, *filled circle* M2, *open circle* M3, *filled triangle* L1, *open triangle* L2, *times symbol* L3

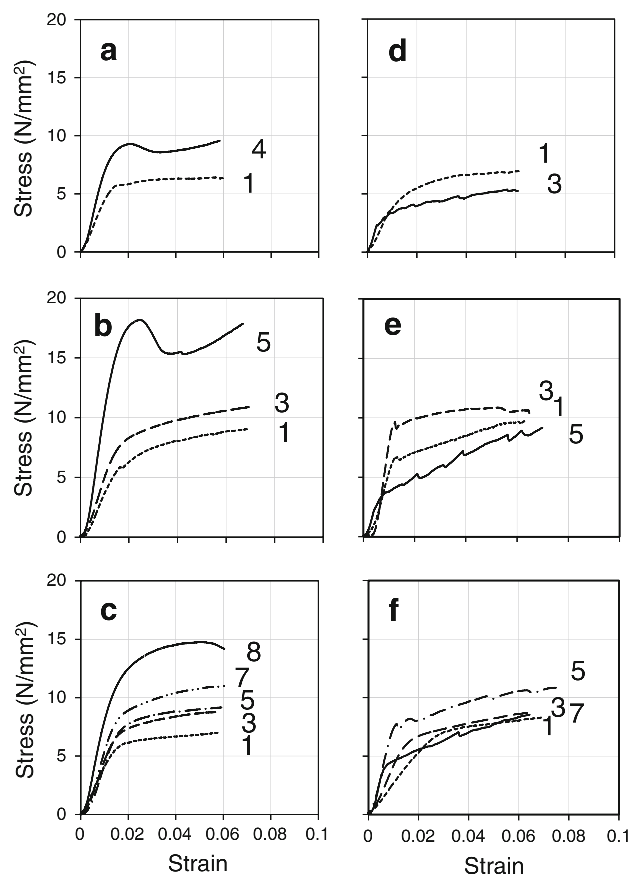


Fig. 5 Typical stress–strain curves of wood samples. **a** Tangential direction of specimens from S3, **b** tangential direction of specimens from M2, **c** tangential direction of specimens from L2, **d** radial direction of specimens from S3, **e** radial direction of specimens from M2, **f** radial direction of specimens from L2; *1*, *3*, *4*, *5*, *7*, and *8*. Sample no. numbered from the pith to the bark

tangential and radial loading directions at different distances from the pith of logs with different diameters. Changes in the shapes of the stress–strain curves with increasing distance from the pith showed different tendency depending on the loading directions. In the tangential loading direction, the proportional limit tended to increase with increasing distance from pith, while in the radial direction, the proportional limits of specimens near the pith were not always lower than those near the bark.

Figure 6 shows the relationship between the distance from the pith and $\sigma_{5\%}$ in the tangential and radial loading directions. From this figure, it is evident that the changes in $\sigma_{5\%}$ from the pith to the bark differed depending on the loading direction. In the tangential loading direction, $\sigma_{5\%}$ tended to increase with the distance from the pith. However, such an increase in $\sigma_{5\%}$ with the distance from the pith was not observed in the radial loading direction. $\sigma_{5\%}$ in the radial loading direction peaked between the pith and the bark, or decreased near the bark.

Nagaishi et al. [8] investigated the radial variation in the partial compression properties perpendicular to the grain of Obi-Sugi and reported that $\sigma_{5\%}$ in both the tangential and radial loading directions was higher in juvenile wood that contained a pith than in mature wood. They inferred that higher values of $\sigma_{5\%}$ can be attributed to the higher air-dried wood density in juvenile wood. Nakai and Yamai [14] investigated the mechanical properties of 35 important Japanese woods and reported that the air-dried densities and $\sigma_{5\%}$ in the tangential loading direction were linearly correlated in both softwood and hardwood.

Figure 7 shows the relationship between $\sigma_{5\%}$ in the tangential and radial loading directions and the density of the air-dried wood specimens obtained from logs with different diameters. The value of $\sigma_{5\%}$ in the tangential loading direction increased with the air-dried wood density (Fig. 7a–c), which is similar to the results reported by Nakai and Yamai [14]. On the other hand, $\sigma_{5\%}$ in the radial loading direction does not correlate with the air-dried wood density (Fig. 7d–f).

The results shown in Figs. 5 and 6 indicate that the radial variation in $\sigma_{5\%}$ was anisotropic in the tangential and radial loading directions. They also indicate that the radial variation in $\sigma_{5\%}$ differs from that in the case of Obi-sugi as reported by Nagaishi et al. [8].

Figure 8 shows the relationship between $\sigma_{5\%}$ and ARW of wood specimens obtained from logs with different diameters; $\sigma_{5\%}$ values did not significantly correlate with the ARW in either loading direction, but $\sigma_{5\%}$ in the

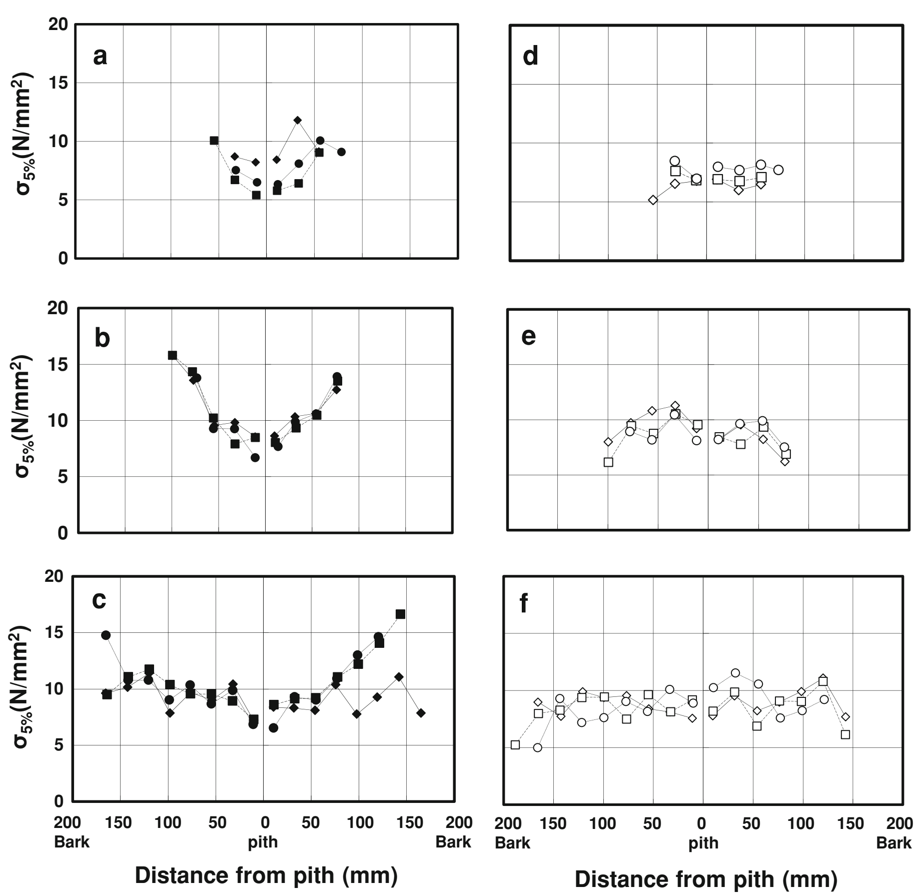


Fig. 6 Relationship between $\sigma_{5\%}$ and distance from pith. **a** Tangential direction of specimens from S3, **b** tangential direction of specimens from M2, **c** tangential direction of specimens from L2, **d** radial direction of specimens from S3, **e** radial direction of specimens from M2, **f** radial direction of specimens from L2. *Filled diamond* T1, *filled square* T2, *filled circle* T3, *open diamond* R1, *open square* R2, *open circle* R3, *T* specimen for partial compression test in the tangential direction, *R* specimen for partial compression test in the radial direction

tangential loading direction tended to slightly increase and that in the radial loading direction tended to slightly decrease with decreasing ARW.

As shown in Figs. 7 and 8, $\sigma_{5\%}$ in the tangential loading direction tended to increase with increasing air-dried wood density and with decreasing ARW, whereas $\sigma_{5\%}$ in the radial loading direction tended to be low in wood specimens that had small ARW. These results indicate that the factors affecting $\sigma_{5\%}$ would be different under different loading directions.

Ido et al. [11] reported that $\sigma_{5\%}$ in the tangential direction was higher than that in the radial direction in four tested wood species (Japanese cedar, Japanese larch, Japanese red pine, and Dahurian larch) and attributed this anisotropy of partial compression properties to the mechanisms of compression perpendicular to the grain [15]. They indicated the possibility that compression in the tangential direction would result in buckling of the latewood zone and that compression in the radial direction would result in crushing failure in the earlywood zone because latewood generally has higher density and strength than earlywood.

It is difficult to conclude the reason for the radial variations in $\sigma_{5\%}$ (Fig. 6) because many factors affect the partial compression properties perpendicular to the grain [16, 17]. However, if the radial variations in the partial compression properties perpendicular to the grain are significantly affected by the radial variations in the

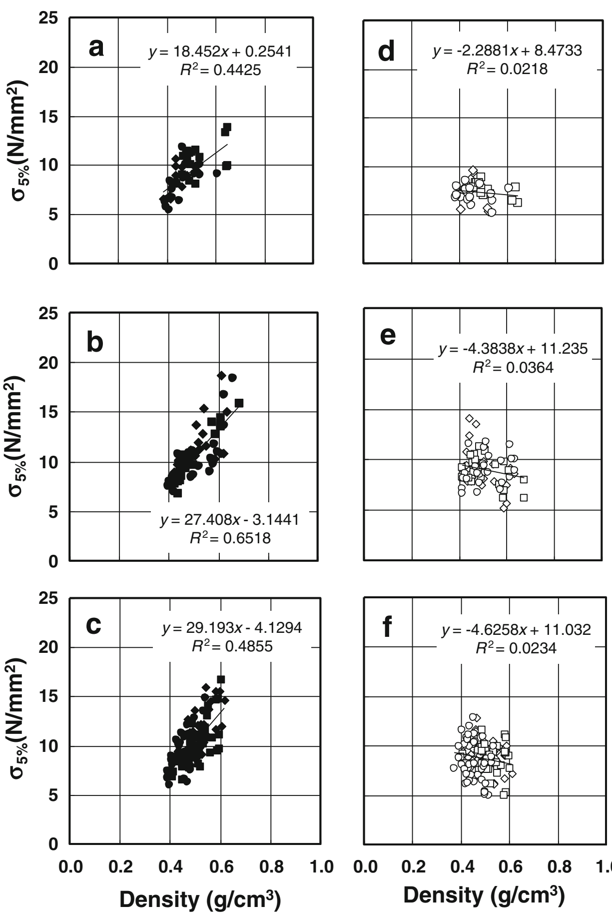


Fig. 7 Relationship between $\sigma_{5\%}$ and air-dried wood densities. **a** Tangential direction of specimens from small-diameter logs, **b** tangential direction of specimens from medium-diameter logs, **c** tangential direction of specimens from large-diameter logs, **d** radial direction of specimens from small-diameter logs, **e** radial direction of specimens from medium-diameter logs, **f** radial direction of specimens from large-diameter logs. *Density* air-dried wood density, *filled diamonds* specimens from S1(a), M1(b), L1(c); *open diamonds* specimens from S1(d), M1(e), L1(f); *filled squares* specimens from S2(a), M2(b), L2(c); *open squares* specimens from S2(d), M2(e), L2(f); *filled circles* specimens from S3(a), M3(b), L3(c); *open circles* specimens from S3(d), M3(e), L3(f)

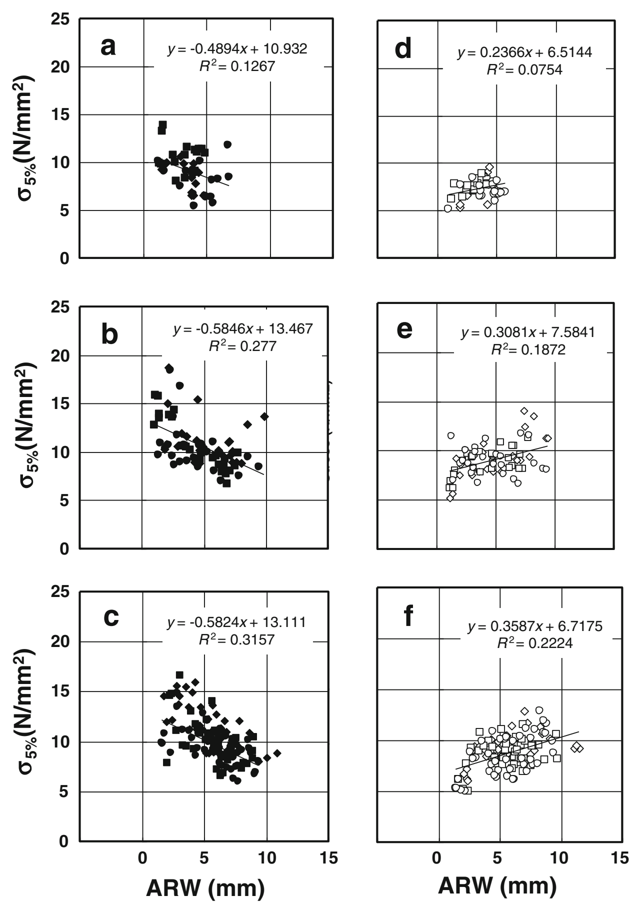


Fig. 8 Relationship between $\sigma_{5\%}$ and ARW. **a** Tangential direction of specimens from small-diameter logs, **b** tangential direction of specimens from medium-diameter logs, **c** tangential direction of specimens from large-diameter logs, **d** radial direction of specimens from small-diameter logs, **e** radial direction of specimens from medium-diameter logs, **f** radial direction of specimens from large-diameter logs. *Filled diamonds* specimens from S1(a), M1(b), L1(c); *open diamonds* specimens from S1(d), M1(e), L1(f); *filled squares* specimens from S2(a), M2(b), L2(c); *open squares* specimens from S2(d), M2(e), L2(f); *filled circles* specimens from S3(a), M3(b), L3(c); *open circles* specimens from S3(d), M3(e), L3(f)

compression properties in transverse directions, we may be able to interpret the radial variation in $\sigma_{5\%}$ on the basis of the mechanism of the compression in transverse directions.

Assuming that the wood consists of earlywood and latewood parts, the compression properties in the tangential loading direction of wood specimens would be affected by the properties both of the earlywood and latewood parts. It is reported that in Japanese larch, the latewood percentage and latewood density increase, the earlywood density tends to remain almost stable, and the average wood density within a ring increases with the distance from the pith [12]. These changes in the structure of the annual rings—the increase in the latewood percentage and latewood density—indicate an increase in the ratio of the part with high densities in the wood, and this increase would, therefore, give rise to an increase in the compression properties of wood in the tangential loading direction. This may explain the increase in $\sigma_{5\%}$ in the tangential loading directions with the distance from the pith (Fig. 6a–c) and with air-dried density (Fig. 7a–c).

It is reported that in the radial loading direction, compression caused the destruction of the tracheid in the earlywood [18–23], and some researchers [19, 21, 22] have reported that the first break upon application of radial compression appears at tracheids in earlywood where the lumen diameter is large and cell-wall thickness is low near the boundary of the annual rings. In Japanese larch, the earlywood density tends to be almost stable, while the average wood density within a ring increases with an increase in the distance from the pith [12]. This means that the radial variation in earlywood density does not significantly correlate with the radial variation in the density of wood and indicates the possibility that crushing failure in the earlywood may not be closely related to the increase in the density of wood. This may explain the reason why $\sigma_{5\%}$ in the radial direction does not increase with an increase in the distance from the pith (Fig. 6d–f) and does not correlate with the air-dried wood density (Fig. 7d–f).

The difference between the radial variations in the structures of annual rings of Japanese larch [12] and Japanese cedar [1, 5, 24] may also explain the difference between the tendencies of radial variations in their partial compression properties. However, anatomical factors such as the shapes of wood cells [25–29], ray volumes [30], and contents of extractives [31] are also reported to affect the mechanical properties in the transverse direction and the radial variations of these structures are also expected to influence the compression properties. Moreover, it is reported that the partial compression properties perpendicular to the grain are affected by complex properties in addition to the compression properties in the transverse direction [16, 17]. To clarify the relationship between $\sigma_{5\%}$ and the structures of wood, more detailed investigations are needed.

Conclusion

The density, ARW, and $\sigma_{5\%}$ of air-dried wood specimens, which were continuous in the radial direction from the pith and were obtained from trees with different diameters in the same stand, were investigated to study the radial variation in the partial compression properties perpendicular to the grain of Japanese larch. The following conclusions were drawn:

1. The density of the air-dried wood specimens increased with the distance from the pith. On the other hand, the ARW tended to decrease with increasing distance from the pith, and a maximum ARW tended to be observed within several rings from the pith in medium- and large-diameter trees.
2. The value of $\sigma_{5\%}$ in the tangential loading direction tended to increase with the distance from the pith. On the other hand, $\sigma_{5\%}$ in the radial loading direction either peaked between the pith and the bark or decreased near the bark. These results indicate that variations in $\sigma_{5\%}$ with increasing distance from the pith exhibit anisotropy in the loading directions.
3. $\sigma_{5\%}$ in the tangential loading direction increased with increasing air-dried wood density and tended to increase with decreasing ARW. $\sigma_{5\%}$ values in the radial loading direction were not significantly correlated with the air-dried wood density and tended to be low in specimens with small ARW. These results indicate that the factors affecting the variations in $\sigma_{5\%}$ with increasing distance from the pith would differ under different loading directions. Changes in the structures of the annual rings of the air-dried wood specimens are thought to result in the anisotropy of variation in $\sigma_{5\%}$ with increasing distance from pith.

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